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ORIGINAL PAPER

Early performance of *Pinus radiata* provenances in the earthquake-ravaged dry river valley area of Sichuan, southwest China

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Abstract: A provenance experiment involving five native provenances and an Australian landrace of *Pinus radiata* (D. Don) was established over three sites in the dry river valley area of Sichuan, southwest China in 2004 in order to select the most suitable provenance for environmental planting on the dry, steep and degraded slopes to reduce soil erosion. Although with much lower soil moisture supply and mean minimum temperatures in winter compared to *P. radiata* provenance trials established elsewhere in the world, these sites are within the working limits of the species defined by previous climate modelling and matching. Because of the difficult site conditions and severe natural disturbances after the experiment was established, mortality was high across the three sites in comparison to provenance trials in other countries. The average mortality rate among the provenance by replicate planting units over the three sites varied from 16% to 76% four years after planting, and from 40% to 88% five years after planting . The repeated measurements of tree size over time were analysed using multilevel linear mixed models to derive growth curves for the mean, median, the 75th and the 90th percentiles of the size distribution of each provenance at each site. There were significant site effects on tree growth, but no significant interactions between site and provenance was detected. Among the six provenances, Cambria was the best performer in diameter, height and stem volume growth across all sites. The better than average and the best trees of this provenance, as represented by the 75th and 90th percentiles of the nominal stem volume distribution, were significantly larger than the Australian landrace, Año Nuevo, and the two island provenances, Guadalupe and Cedros. Monterey was overall the second best performer behind Cambria. The Australian landrace, Guadalupe and Año Nuevo had similar performances in general. Cedros was significantly and consistently inferior to all other native provenances and the Australian land race. Because the genetic base of the present Australian plantations was derived largely from Año Nuevo and Monterey, the superior early growth performance of Cambria at such difficult sites brings a new promise to the search of *P. radiata* provenances for the vast dryland areas in New South Wales and other parts of Australia.

Keywords: *Pinus radiata;* dryland; provenance performance; multilevel linear mixed models; repeated measures analysis

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Introduction

Pinus radiata (D. Don), a native species to the central coast of California, United States and to two Mexican islands off Baja California, was first introduced to the summer rainfall environments of Sichuan Province, southwest China in 1990 as part of research to select the most suitable species for afforestation for soil and water conservation in the arid and semi-arid river valley area of Aba Prefecture (Bi et al. 2003). This area covers the epicentre of the magnitude 8.0 Wenchuan earthquake that struck northwestern Sichuan on Monday 12 May 2008. Among a num-

ber of native as well as exotic species that were tested in planting trials in this area, *P. radiata* had the lowest mortality and the best growth rates during early establishment where native forest species were difficult to establish (Bi et al. 2003; Wu et al. 2005). Although the growth rates are low by commercial standards, mean total stand biomass of 5-year old *P. radiata* plantations was found to be about 12 times greater than that of plantations of the best performing native conifers *P. tabulaeformis* and *Cupressus chengiana* at the same age (Pan et al. 2005). The superiority in growth performance of *P. radiata*, albeit during early plantation establishment, has made it the species of choice for environmental plantings in the dry river valley area (Wu et al. 2005). Within this area a total of 26,000 ha, mostly below 1500 m in elevation, has been identified through climate matching as suitable and a further 63,000 ha, between 1500 and 2000 m in elevation, potentially suitable for environmental plantings of *P. radiata* (Yan et al. 2006). Before the Wenchuan earthquake struck, more than 2000 ha were planted in widely separated small patches on the steep and degraded slopes along the dry river valley (Liu et al. 2005; Yan et al. 2007; Zhou et al. 2010). The planting will be further expanded to cover much of the degraded area according to the current plan of afforestation as part of China's sloping land conversion program (*cf.* SFA 2003; Bennett 2008). These plantations will also in time represent an important part of the shelterbelt forests development program along the upper reaches of Yangtze River (Anonymous 1995; Li 2004).

The extant native forest of *P. radiata* is represented by only five physically disjunct populations: three along the central coast of California (Año Nuevo, Monterey and Cambia) and two on Mexican islands off Baja California, with a total area of less than 6,000 ha according to the latest estimates (Rogers 2002, 2004). Although these native populations are small in total area and have a restricted range and fragmented natural distribution, the species has modest to average levels of genetic diversity and high genetic differentiation among populations compared with other western North American pine species (Rogers 2002; Rogers et al. 2006). In 1978 a comprehensive seed collection in the five natural populations was undertaken by a combined Australia, New Zealand and USA team (Eldridge 1979). This collection enabled systematic assessments of the growth performance of *P. radiata* provenances in plantation culture outside its native range in countries including Australia, Chile, Greece, New Zealand, South Africa and Turkey (Toplu et al. 1987, Falkenhagen 1991, Jayawickrama and Balocchi 1993, Matziris 1995, Burdon et al. 1997; Johnson et al. 1997). In Australia and New Zealand alone, a total of 115 provenance trials and genetic conservation plantings of *P. radiata* have been established using seeds collected in the native stands (Eldridge 1997a, b; Burdon et al. 1998). These trials revealed a large amount of genetic variation in terms of growth rate, form, disease resistance, drought tolerance and resistance to frost damage (Burdon 1992; Eldridge 1997a, b). There also is a high degree of provenance and environment interaction (Ades and Garnier-Gere 1997). Over a range of sites well-suited to growing *P. radiata*, Monterey and Año Nuevo are generally the best of the five native populations for growth rate. However, on more difficult and less productive sites, a clear pattern has not emerged. For sites that are almost too cold for radiata pine, the Año Nuevo provenance is clearly the most cold-tolerant (Burdon 1992). In Ireland and southern England where *P. radiata* is on the limits of its frost tolerance, the Guadalupe population is the healthiest. In the Basque country of northern Spain, the Año Nuevo provenance was less affected by the unfavourable climatic conditions in winter, although the Monterey population showed the best overall performance among the three mainland provenances (Espinel et al. 1995; Aragones et al. 1997). For marginal sites with infertile shallow soils and low rainfall, the Monterey population is sometimes superior in growth to Año Nuevo. At an extreme site in the mid-north of South Australia, about 200 km north of Adelaide, the growth of the Guadalupe provenance was equal to that of Monterey and Año Nuevo, Cambria was next and Cedros was inferior. Over a wide range of sites in New South Wales, Australia, the Cambria provenance was slightly superior in growth rate to the other four on two of the worst sites (Johnson et al. 1997).

The first lot of *P. radiata* seeds introduced to the dry river valley area for the experiment came from a seed orchard of New Zealand Forest Research Institute. Seeds for subsequent plantings were purchased from commercial seed suppliers in China who sourced from either New Zealand or Australia without any specific information on their genetic origin, and so the planted trees are from unknown and possibly inferior genetic stock. To ensure maximum success of the reforestation program in the long run, it is essential to have the best available germplasm that is suitable to the site conditions. The dry river valley goes through a mountainous area where elevation ranges from 1,000 m at the floor of the lower stretch of the valley to above 4,000 m at the highest mountain summits. Due to the mountainous topography, climate variations are more pronounced with complex spatial patterns. The high elevation areas have a characteristically vertical environmental and climatic gradient and associated changes in vegetation types (Yan et al. 2006; Ni et al. 2008). Climate modelling and matching has defined the working limits of *P. radiata* in the dry valley area in the short term (Yan et al. 2006). Provenance testing in field trials will lead to the identification of the best sources of genetic material for growth, drought and frost tolerance, and resistance to pests and diseases in the long run. In 2004 a provenance experiment was established over three sites in the dry river valley area. This paper reports the survival and compares the early growth performance of six *P. radiata* provenances six years since germination and five years after planting.

Materials and methods

Study area

The dry river valley area in the Aba prefecture of Sichuan province in southwest China lies within longitude 102°37′–103°58′ E and latitude 30°50′–33°10′ N, and stretches over 150 km through five counties along the upper reaches of the Minjiang River, a tributary of the upper Yangtze River in northwestern Sichuan. Much of this mountainous area is administrated by three adjacent

counties: Wenchuan, Lixian and Maoxian, where ecosystem degradation led to a vulnerable arid and semi-arid river valley environment plagued by soil erosion and landslides down the steep slopes long before the 2008 earthquake struck (Bi et al. 2003; Yan et al. 2006; Li et al. 2006; Bi et al. 2008). The arid and semi-arid environment that characterises the dry river valley has been gradually expanding and at present is largely confined to areas with elevation below 2,900 m (Yang et al. 2007). The mean annual evaporation in this area is more than three times greater than the mean annual rainfall. The lower stretch of the dry river valley in Wenchuan has a mean annual rainfall above 500 mm, a mean annual temperature of about 14°C and about 260 frost free days. The middle stretch in Lixian is the most arid, and has a mean annual rainfall of about 370 mm, a mean annual temperature of about 13°C and 255 frost free days. The upper stretch in Maoxian is the coldest. It has a mean annual rainfall of about 500 mm, a mean annual temperature of about 11°C and 216 frost free days (Yan et al. 2006). The extreme minimum temperature recorded in the county town was below -10°C during winter in early 2008. About 80% of the annual rainfall in this region falls during the summer months between May and October. Over the entire course of the dry river valley, extreme minimum temperatures and moisture supply were identified to be the limiting climatic factors for *P. radiata* (Yan et al. 2006).

Seed sources, experimental design and establishment

The experiment included five *P. radiata* provenances and an Australian landrace (Table 1). Seeds of the Año Nuevo, Monterey, Cambria, Cedros provenances were collected from the native populations in 1978 (Eldridge 1978, 1979). For the Guadalupe provenance, open-pollinated seeds with local male and Guadalupe female parents were collected from a provenance planting in Canberra, Australia. Seeds of the Australian landrace were collected in the 1980s' from the first-generation Tallaganda Seed Orchard (TSO) in southeastern New South Wales, where the mean annual precipitation is 1300 mm (Pook et al. 1991). This orchard was established on clay loam soil by planting 1020 grafts or rooted cuttings of 30 plus trees at a spacing of 6.1 m × 6.1 m (Fielding 1964; Eldridge 1982). These trees were selected for their large size and straight form, and good branching habit in plantations more than 20 years old near Canberra. The genetic base of these plantations was from only Año Nuevo and Monterey, the two supposedly best-adapted of the five natural populations as reported for other present Australian and New Zealand plantations (Moran and Bell 1987; Burdon 1992; Wu et al. 2007).

Table 1. Location and other attributes of the five native *P. radiata* provenances and the Tallaganda Seed Orchard (TSO) from which seeds of the Australian landrace were collected

Provenance	Code	Latitude	Longitude	Altitude (m)	Soil	Mean annual rainfall (mm)
Año Nuevo	1	37.0 °N	122.5°E	10-330	Fine loams derived from argillites	800
Monterey	2	36.5 °N	122.0°E	10-440	Very varied fertility and base status	400
Cambria	3	35.5 °N	121.0°E	10-200	Sandy loam with localized poor drainage	500
Cedros	4	28.0 °N	115.3°E	290-640	Generally skeletal	150
Guadalupe	5	29.0 °N	118.3°E	330-1200	Rocky loam on basalts	150
Tallaganda Seed Orchard	6	35.7°S	149.5°E	900	Clay loam	1300

A total of more than 20,000 seeds, unequally shared by the six provenances, were obtained from Dr. Ken Eldridge of the former CSIRO Division of Forestry and Forest Products for the experiment. Seedlings were individually raised in large plastic containers at a temporary forestry nursery set up specifically for the purpose of the experiment at Yingxiu town of Wenchuan County in early 2003. Yingxiu was the epicentre of the devastating earthquake that took place in 2008. The number of seeds, their germination rate, and the number and average size of the seedlings at the nursery before planting in early 2004 were summarized for each provenance in Table 2.

Three experimental sites were selected at the lower, middle and upper stretches of the dry river valley in Wenchuan, Lixian and Maoxian to represent the full range of topographic features, environmental and site conditions along the valley (Table 3). The first site was approximately 2.95 ha in size over a mid- to upper slope at Zaojiaotuo of Yinxing township of Wenchuan along the lower stretch of the valley. This site was covered by dense grass and shrubs since it had been abandoned for some time as a marginal farmland with some fruit trees intercropped with vegetables and other crops. During site preparation the shrubs and weeds were slashed before terraces were made along the slope contours. Pits about 50 cm in diameter and 40 cm in depth were then dug along each terrace at approximately 2 m intervals to prepare for planting. The second site was approximately 2.87 ha in size over the mid to lower sections of a very steep and exposed slope at Nangou of Xuecheng town of Lixian along the middle stretch of the valley (Table 3). The area was dissected by gullies that were formed by soil erosion and orientated down the main slope. Representing a typical arid environment of the dry river valley, this site is the most arid out of the three sites, where soil moisture content in the layer of soil between 0 and 30 cm could be less than 10% for the whole year (Yan et al. 2006). The soil moisture conditions were also reflected by the relatively sparse cover of dwarf semi-shrub and grass vegetation. As with the first site terraces were constructed manually along the slope contours by cutting the uphill side and moving the soil to fill the downhill side. Planting pits were dug along the terraces in the same way. The third site was approximately 2.70 ha in size over a lower slope along the upper stretch of the dry river valley in Maoxian. This site had just been planted with *Cupressus chengiana* and the seedlings were mostly less than 0.5 m in height. Because sites of large enough area with relatively uniform site conditions were very limited, this site was converted for the provenance experi-

ment. The site was covered by very low grasses with few shrubs largely because of the site preparation for the previous tree planting and on-going grazing by livestock. Among the three sites, this site is the flattest and also the best in terms of soil fertility and soil moisture condition, partly due to seepage down slope. The soils at the three sites corresponded to a cinnamonic type which, in the dry river valley area, is characterized by low weathering intensity and argillication, high calcium carbonate ($CaCO_3$) mass fraction with pH falling between 8.0 and 9.0. Because of the low soil moisture content, the saline and alkali soils are low in available soil nitrogen, phosphorus and potassium (Wang et al. 2003).

Table 2. The number of seeds, their germination rate, and the number of seedlings raised for each provenance. The average diameter and height, and their standard deviations (STD) were calculated from a random sample of 60 seedlings taken for each provenance at the nursery just before planting.

Provenance	Code	No. of seeds	Germination rate (%)	No. of seedlings	D (cm)	STD of D	H (cm)	STD of H
Año Nuevo	1	4479	49.1	2121	0.33	0.049	25.6	3.23
Monterey	2	5557	44.6	2433	0.43	0.078	30.2	4.14
Cambria	3	3666	41.7	1508	0.48	0.068	31.6	3.84
Cedros	4	2226	21.6	473	0.24	0.043	15.9	4.31
Guadalupe	5	2659	72.0	1872	0.35	0.050	27.5	3.55
TSO	6	1444	67.7	949	0.37	0.048	28.7	3.28
Total		20031		9356				

Table 3. Locations and site characteristics of the three experimental sites

Site	County	Township	Location	Latitude N	Longitude E	Elevation (m)	Slope	Aspect	Topography
1	Wenchuan	Yinxing	Zaojiaotuo	30°30’	103°13’	1200	27.5°	SW, sunny	mid to upper slope
2	Lixian	Xuecheng	Nangou	31°32’	103°19’	1600	40.5°	S, semi-shady	mid to lower slope
3	Maoxian	Fengyi	Malianggou	31°42’	103°52’	1800	20.0°	SW, semi-shady	lower slope

Site	MAR (mm)	MAE (mm)	MAT	MAXT	MINT	Soil depth (cm)	Soil type
1	529	1433	14.5°C	35.5°C	-5.1°C	40	cobble and gray-cinnamonic soil
2	370	1436	11.6°C	33.6°C	-9.3°C	45	gravally clinosol & light loamy gray-cinnamonic soil
3	500	1441	11.6°C	31.6°C	-9.5°C	50	Cobble & medium loamy gray-cinnamonic soil

Site	Native vegetation and major shrub species	
1	Low shrub:	*Bauhinia faberi var. microphylla, Sophora viciifolia, Jasminum humile*
2	Dwarf semi-shrub:	*Convolvulus tragacanthoides, Ajania potaninii, Ajania breviloba, Sophora viciifolia*
3	Tall Shrub:	*Cotinus coggygria, Prunus tangutica, Hippophae rhamnoides, Ostryopsis davidiana*

MAR- Mean annual rainfall; MAE- Mean annual evaporation; MAT- Mean annual temperature; MAXT: Mean annual maximum temperature; MINT: Mean annual minimum temperature.

Three blocks were laid out for three replications at the first and third site. The blocks were not equal in size because the layout accommodated local topographic variations, slope contours and other site features such as gullies, drainage lines and patches of native shrubs. Within each replicating block six plots were randomly located for the six provenances. Because the number of seedlings available for planting differed among provenances, plot size varied to some degree but the spacing remained relatively constant at approximately 2 m × 3 m. At the second site in Lixian, four blocks were laid out to accommodate the slopes and gullies over the site area. The four blocks consisted of 25, 37, 33 and 15 terraces each running from lower to upper slope positions within the site area. Due to the steepness of this site and the systematic change of soil water content along the slope (Yan et al. 2006), a block was not divided into 6 plots like the other two sites. Within a replicating block, each terrace was used as a planting row and assigned to a provenance at random so that the effects of slope positions on provenance performance could be reduced. Surplus seedlings were planted along the top edge of the experimental site to form a narrow buffer zone. Seedlings were hand planted at all sites without fertilization in late March and early April, 2004. At the second site, small pieces of slate stone that were readily available on site were placed around the seedlings after planting to cover the soil to reduce the loss of moisture, which was a proven effective local planting technique (Zheng et al. 2005). In total, there were more than 5,100 seedlings planted over the three sites, which also included more than 600 surplus seedlings planted at the third site in areas surrounding or immediately adjacent to the designated experimental blocks. Since there were a relatively smaller number of seedlings for provenances 4 and 6 (Table 2), the surplus seedlings only included provenances 1, 2, 3 and 5. These trees were used

as the forth replicate at this site later in the analysis. To protect the sites against animal browsing and other damages, fences were erected around the perimeter of each site with concrete poles strung with barbed wire.

Field measurements, experiment maintenance and natural disturbances

Survival at three months after planting was well over 90% when the three experimental sites were inspected in early July, 2004, and the new shoots were generally between 15 cm and 20 cm in length. A year after planting, seedlings at each site were mapped and tagged so that they could be individually identified in subsequent annual measurements in winter. At the first measurement in the winter of 2005 when the seedlings were effectively 2 years old since they had grown over two growing seasons, there were 2223, 945 and 1966 seedlings (including the surplus plantings) at the first, second and third site respectively. Thereafter measurements were taken annually in winter well after the growing season of the year ended. Diameter at ground level and tree height were measured at each measurement. Once seedlings were taller than 1.3 m, diameter at breast height (DBH) was also measured. Dead seedlings were recorded and damages caused by animal browsing, frost, insect defoliation, diseases and other reasons were noted for individual seedlings. The surplus seedlings planted at the third site were also measured in the same way at each measurement, but those at the second site were not measured. By the end of 2008, the experiment had been measured four times at effective ages of 3, 4, 5 and 6 years since germination, providing data for the evaluation of survival and early growth of the six provenances.

There were a number of problems caused by weeds, insect infestation, animal browsing, extreme weather conditions and earth quake during the course of the experiment. Weeds were identified as a problem affecting seedling survival and growth at the first site in the first three years after planting. As a measure of weed control, the shrubs and weeds surrounding individual seedlings were manually slashed in summer to prevent the planted seedlings from being overtopped. Although a great deal of care was taken during this silvicultural treatment, a small number of seedlings were accidentally slashed. In the summer of 2005, a localised outbreak of *Nesodiprion* sp. (pine sawfly) caused defoliation to some of the 1-year old trees at the first site (Bi et al. 2008). Some trees were so severely defoliated that they did not put on enough growth to survive through the following winter. Infestation of this sawfly was also detected at the third site in Maoxian, causing minor defoliation to some trees. Subsequent monitoring revealed that the outbreak tended to take place from late July to early August. Protective treatments and chemical control were applied to prevent any further infestation and damage at the two sites in later years. At the second site in 2005, needle blight was observed to have occurred to more than 20 seedlings, which weakened their growth vigor, but did not result in mortality. During winter in early 2005, barbed wire fences surrounding the third site were cut and stolen, which rendered the experimental site completely open to livestock. Animal browsing caused significant damage to parts of the experiment. To prevent animal browsing in subsequent years, the Maoxian Forestry Bureau built a small temporary cottage next to the experimental site so that two guards could be stationed there in winter protecting the site during the day. However, animal browsing still occurred in subsequent years to a minor degree, but the damage was much reduced. At the second site in Lixian, some seedlings in the buffer zone along the top edge of the experimental site were grazed by a local species of rock mice in winter, but no major damage was caused to the seedlings in the experimental blocks.

In 2006 an unusually prolonged summer drought occurred in the dry river valley area. The second site was the most affected among the three sites. According to the meteorology bureau of Lixian, the drought lasted 55 days in the growing season from mid July to early September, and the total rainfall was only 35.9 mm over this period. In early 2008, starting on 25 January until 6 February 2008, a series of snowstorms swept through large parts of southern and central China with heavy snows, ice and low temperatures, making it the worst snowstorm in China in more than half a century. The daily minimum temperature recorded by the meteorology bureau of Maoxian in the town centre was below -10°C for three consecutive days (Fig. 1).

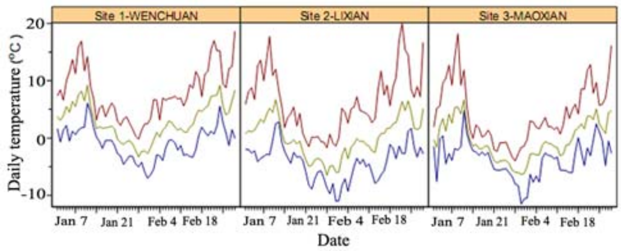

Fig. 1 Daily maximum, mean and minimum temperatures in Wenchuan, Lixian and Maoxian during the snowstorms that swept through large parts of southern and central China in early 2008

An even lower daily minimum temperature was expected at the third site in Maoxian because of its exposure to strong wind from the gulley in winter. Among the three sites, this site was the worst affected and all trees suffered from severe frost damage. However, most trees recovered later in spring. A detailed assessment of the frost damage was planned, but not carried out due to the devastating earthquake in May, 2008. The earthquake caused major damages to two experimental sites closest to the epicentre. The first site at Yinxing in Wenchuan was only about 10 km from the epicentre. Because of this close proximity, many cracks were opened up in the ground by the earthquake, causing damages to the roots. Trees suffered a great deal of mortality possibly because of the damages to the roots as well as the loss of soil moisture through the cracks. When assessed in 2009 most of the trees on this site were dead. The second site at Xuecheng in Lixian was about 60 km from the epicentre. A small section on the edge of the experimental site was buried by a landslide down the steep slope during the earthquake. Many trees in other parts of the experiment were damaged by rocks rolling down the slope during the earthquake. These natural disturbances were

identified to be the major cause of mortality of the young seedlings across the three sites.

Data Analysis

Data screening

Diameter and height measurements from 2005 to 2008 were screened through graphical exploratory analysis which included scatter plots, frequency distribution histograms, and box-plots to detect possible measurement and data entry errors (Fig. 2). For the same purpose, height and diameter ratio was calculated for all individual trees and screened in the same way. A number of erroneous data points were detected and corrected. A small number of trees had missing values of either diameter or height measurements. For these trees, their missing measurements were estimated by simple linear relationships between log transformed diameter and height developed for their specific site, provenance, block and age through linear least-squares regression. The merits of regression imputation as a method to handle missing data were discussed in detail in Gelman and Hill (2007).

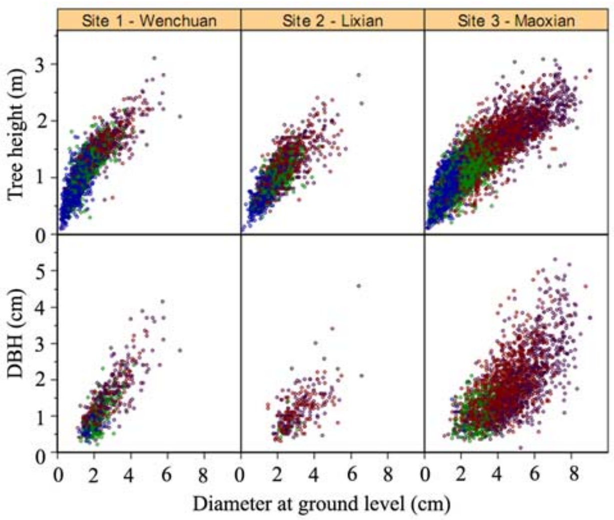

Fig. 2 Height and DBH in relation to diameter at ground level of individual trees at the three experimental sites. Measurements taken at different ages were shown in different colors**.**

Mortality

Mortality was calculated for two consecutive years of 2007 and 2008, before and after the earthquake, as the percentage of seedlings that had died since the first measurement in 2005 for each provenance at each site. Since seedling mortality was caused largely by natural disturbances including overtopping by weeds, accidental slashing, insect infestation, animal browsing, extreme weather conditions and earth quake during the course of the experiment, mortality rates of the six provenances at each site were summarized but not statistically analysed.

Early growth performance of six provenances

The differences among the six provenances in seedling diameter and height measured just before planting at age one year since germination were quite evident as shown in Table 2. Such initial differences in seedling size would inevitably lead to differences in growth performance among the six provenances at least shortly, if not long, after planting. So the data from 60 seedlings randomly taken for each provenance before planting should naturally be regarded as the first measurements at the starting point of growth and be used together with measurements taken after planting in the analysis of early growth performance of the six provenances. In order to combine the data before and after planting, a random sample of 50 seedlings was taken with replacement from the original pool of 60 seedlings for each combination of site, provenance and replication. This repeated sampling generated data that had the same structure to the field data and therefore mimicked the seedling sizes at the time of planting for each provenance and replicate across the three sites. At the same time the random sampling with replacement also preserved some degree of variation among replicates for each provenance at each site.

The combined data set had a total of 63 site, provenance and replicate combinations, each with 5 measurements available at age 1, 3, 4, 5, and 6 years since germination. Diameter at ground level, tree height and nominal stem volume were the three variables of tree size used for comparing the early growth performance of the six provenances. The reason to use diameter at ground level instead of DBH was that the data for the former was complete and available for all trees at all measurements. For each tree, a nominal stem volume was calculated using the geometrical tree volume equation developed by Forslund (1982) and MacDonald and Forslund (1986). For all three variables of tree size, the mean, median, the 75th and 90th percentiles were calculated for each provenance at each replicating block for every site. So there were 12 calculated tree size variables in total. Although the mean represents the average tree size, it was less resistant to extreme values or outliers in the size distribution. Because of the natural disturbances such as insect defoliation, physical damage during weeding and earthquake, animal browsing and frost damage endured by the young trees at the experimental sites, there were some trees that were much smaller than others of the same provenance within the same replicating block at the same site. The median, being more resistant to such small values in the size distribution, provided an alternative and comparative indicator of 'average' tree size. The upper quartile and the 90th percentile represented the better than average and the best trees in the size distribution, and so were of primary interest in selecting trees for breeding and genetic improvement for environmental planting in the arid and semi-arid environment of the dry river valley.

Out of the 315 plot measurements over 6 years since germination and 5 years since planting, there were a total of 71 measurements across the three sites which had less than 20 trees mostly at the last two measurements. These included 7 plot measurements with no tree survived at the final measurement. These 7 missing observations could not be treated simply as missing at random in multilevel mixed effects models in the analysis described below, but there are no principled non-ignorable missing data methods readily available to most data analysis at present. In addition, the calculated percentiles based

on plot measurements with less than 20 trees were unreliable. To overcome the problems of missing and insufficient data at least partially, tree diameter and height were regressed against age on log scales for each provenance at each site using replicates as dummy variables for intercept. So replicates of the same provenance had a common slope but different intercepts. To obtain an imputed value of tree diameter at a given age for a particular provenance and replicate, a residual was randomly taken from the corresponding regression residuals for the provenance and replicate and added to the predicted value. Then the sum was back transformed from logarithm. Imputed values of tree height were obtained in the same way. For these 71 plot measurements, different numbers of imputed values were obtained so that each plot measurement had at least 20 diameter and height data points. After data imputation, tree size variables were re-calculated as described above.

Statistical analysis

The statistical analysis of the early growth performances of the six provenances went through three stages. At the first stage, each of the 12 calculated tree size variables was related to tree age, site and prevenance through an ordinary least squares regression using indicator variables representing individual sites and provenances. The slight curvatures in tree size in relation to age and the presence of heteroskedasticity in the residuals suggested that logarithmic transformation was necessary for the response variables. For tree age, log transformation was also taken after a comparison of logarithmic, inverse and square root transformations. During this analysis, the interactions between site and age, provenance and age, site and provenance were also explored to gain some preliminary indication on how the mean trend in tree size could be modelled. At the second stage, linear mixed models were employed for both cross-sectional and longitudinal analysis of the experimental data. In the cross-sectional analysis, each of the log transformed tree size variables was related to site, block, and provenance at each age separately. In the longitudinal analysis, these transformed tree size variables were related to block, provenance and tree age for each site separately. Since the three experimental sites were not a random sample from a potentially large number of sites but subjectively selected to represent the typical environmental conditions of the lower, middle and upper reaches of the river valley, their effects on tree growth were assumed to be fixed in the analysis. By contrast, the replicates within a site were taken as random samples and their effects were therefore treated as random that were nested within the site. From these analyses, some further insight was gained on the fixed effects of site, provenance, tree age and possible interactions between them, the magnitude of random effects, and also on the covariance structure for the repeated measurements.

At the final stage, each of the transformed tree size variables was analysed across the three sites and over five ages through a linear mixed effects model, initially with a full specification by including all fixed effects and all possible interactions between them. The models were fitted to the data using the restricted maximum likelihood (REML) method. Unlike the maximum likelihood (ML) method, it produces unbiased estimates of covariance parameters by taking into account the loss of degrees of freedom that results from estimating the fixed effects (West et al. 2007). For data following a balanced mixed linear model, the standard ANOVA method typically gives exact F tests of the hypotheses about fixed effects. However, for unbalanced experiments as in this case, it does not lead to exact tests. So the approximate method proposed by Kenward and Roger (1997) was used to test each of the fixed effects and their interactions based on the type III (marginal) sum of squares. The superiority of the Keward-Roger adjustment to other alternatives has been well demonstrated for blocked experiments with missing values and the analysis of repeated measurements (e.g. Kowalchuk et al. 2004; Spilke et al. 2005). Following these tests, the full model was reduced by iteratively removing non-significant interaction terms before arriving at the final specification. In this analysis, there were a total of 63 subjects (i.e. replicate by provenance combinations): 18 at the first site, 23 and 22 at the second and the third site respectively. For each subject, there were five repeated measurements, resulting in a total of 315 observations.

While the model specification for the mean structure of the fixed effects was determined, the variance and covariance structure for the repeated measures data was also modelled by broadly following the four-stage process outlined by Littell et al. (2000) for the implementation of mixed models. Several variance and covariance structures were compared for all 12 tree size variables using the Akaike information criteria (Akaike 1973) corrected for the finite sample size (AICc) (Sugiura 1978). These included the commonly used unstructured (UN) and the first-order autoregressive structures, AR(1), specified for individual sites and for individual provenances to allow heterogeneous variances for different groups of subjects, and a more detailed subject-specific AR(1) structure. Another frequently used structure, compound symmetry (CS), was not used because it would impose an unrealistic variance and covariance structure i.e. not only a constant residual variance over time like in AR(1) but also a constant covariance between residuals of repeated measurements. After evaluating and comparing a large number of fittings, the site-specific UN structure emerged to be the most appropriate and parsimonious and so was adopted for all variables in the analysis.

The final specification for the multilevel mixed effects model was as follows:

$$y_{hijk} = \mu + \alpha_h + \rho_j + \beta_0 T_{hijk} + \beta_h T_{hijk} + \gamma_{i(h)} + \varepsilon_{hijk} \quad (1)$$

where y_{hijk} denotes the value of a natural log transformed tree size variable at measurement k (k=1, 2, 3, 4, 5) for provenance j (j=1, 2,3,4,5,6) in replicate i (i= 1, 2, 3, 4) of site h (h=1, 2, 3), μ is a constant common to all observations, α_h is a fixed effects parameter for site h, ρ_j is a fixed effects parameter for provenance j, β_0 is a fixed coefficient common to all observations on the continuous covariate T_{hijk} (i.e. natural log transformed tree age), β_h is a fixed coefficient on the same covariate

for site h only, $\gamma_{i(h)}$ is the random effect corresponding to the ith replicate within site h, and ε_{hijk} is a random error. In matrix notation this model specification became

$$Y = X\beta + Z\gamma + \varepsilon \tag{2}$$

where $\boldsymbol{Y}$[315, 1] is the vector of 315 observations, $\boldsymbol{X}$[315, 14] is the treatment design matrix, $\boldsymbol{\beta}$[14, 1] is the vector of fixed effect parameters, $\boldsymbol{Z}$[315, 11] is the site and replicate block design, $\boldsymbol{\gamma}$[11,1] is the vector of random effects, $\boldsymbol{\gamma}$ and $\boldsymbol{\varepsilon}$ follow multivariate normal distributions with zero means and variance and covariance matrices **G** and **R**, i.e. $\gamma \sim N(0, \mathbf{G})$ and $\varepsilon \sim N(0, \mathbf{R})$. The two normally distributed random variables were assumed to be independent of each other, and so Cov[$\boldsymbol{\gamma}$,$\boldsymbol{\varepsilon}$]=0. In this case of random replicate blocks, the eleven random block effects were assumed to be independent with equal variance across sites, and so **G** is a scalar matrix with the same eleven diagonal elements. The **R** matrix is block diagonal with each block corresponding to a subject. For the site-specific UN structure used in this analysis, subjects at the same site had the same block matrix with 15 variance and covariance parameters as follows:

$$\begin{pmatrix} \sigma_1^2 & \sigma_{12} & \sigma_{13} & \sigma_{14} & \sigma_{15} \\ \sigma_{21} & \sigma_2^2 & \sigma_{23} & \sigma_{24} & \sigma_{25} \\ \sigma_{31} & \sigma_{32} & \sigma_3^2 & \sigma_{34} & \sigma_{35} \\ \sigma_{41} & \sigma_{42} & \sigma_{43} & \sigma_4^2 & \sigma_{45} \\ \sigma_{51} & \sigma_{52} & \sigma_{53} & \sigma_{54} & \sigma_5^2 \end{pmatrix}$$

Across the three sites, there were three such matrices and so 45 variance and covariance parameters to be estimated.

The model was initially estimated by using both the RANDOM and REPEATED statements in the mixed procedure of SAS. The estimated value of **G** was very close to, and not significantly greater than zero as indicated by the asymptotic Wald test of the covariance parameter. It was generally smaller than 0.001, with many estimates being even smaller than 0.0001 for the 12 tree size variables. The estimated random effects were not significantly different from zero as indicated by the asymptotic t-test. When both the RANDOM and REPEATED statements were used with an unstructured variance and covariance structure in the procedure, the between-subject random variation was modelled twice in both **G** and the diagonal elements of **R.** Such redundancy was removed in the final analysis by modelling the variation of both the random effects and the random error in terms of **R** by setting **G**=**0** and using only the REPEATED statement. Littell et al. (2000) and Liu et al. (2007) provided additional details on how to use the RANDOM and REPEATED statements in modelling covariance structure in the analysis of repeated measures data.

The fixed effects of site, provenance, age and the interaction between site and age were each tested with an F-statistic at first. For the effects of site and provenance, the corresponding null hypotheses were that there were no differences in tree size among the three experimental sites and among the six provenances. Following the tests of the overall null hypotheses, pairwise comparisons of the least squares means at age 1 and 6 years were performed for the three sites and for the six provenances. Because of the unequal sample size among the three sites and the six provenances, the Tukey-Kramer method was used to compute p-values for all pairwise comparisons. Asymptotic t-test was used to examine the difference in the values of the coefficients associated with the covariate of tree age and the interaction between site and age. Unless otherwise stated, a standard level of statistical significance at α=0.05 was used throughout these tests. In addition to these statistical tests, site-level and provenance-level growth curves were drawn using the fixed effect parameter estimates for the mean, median, the 75th and the 90th percentile of all three tree size variables after back transformation from logarithm. The purpose of these curves was to illustrate how the growth patterns differed among the three sites and among the provenances across sites.

Results

Mortality

In 2007, before the snowstorms and the earthquake struck, the highest mortality rate was observed at the first site in Wenchuan, which ranged from 52% to 100% with an average of 75.6% among the18 provenance by replicate planting units (Fig. 3). Mortality at the second site in Lixian varied between 0 and 65.5% with an average of 29.9% among the 23 units, and that at the third site in Maoxian varied between 2.9% to 44.1% with an average of 16.4% among the 22 planting units. Among the six provenances, Cedros had the highest average mortality of 44%, within a wide range of 15% to 100% among the 9 planting units across the three sites. The average mortality for the Australian land race was 41% within a range of 3% to 96%. Año Nuevo, Monterey and Guadalupe had similar levels of average mortality between 36% and 39% within a range of less than 5% to more than 90%. Cambria had the lowest average mortality of 32% within a relatively narrow range of 8 to 64% among its 11 planting units across the three sites.

After the snowstorms and earthquake struck in 2008, mortality increased substantially across the three sites (Fig. 4). The average mortality among the planting units reached almost 88% at the first site in Wenchuan, 57% at the second site in Lixian and 49% at the third site in Maoxian. Among the six provenances, Cedros had the highest average mortality of 74%, within a wide range of 20% to 100% among the 9 planting units across the three sites. The average mortality for the Australian land race was 67% within a range of 15% to 100%, and that for Guadalupe was 64% within a range of 29% to 100%. Monterey and Cambria had the same average mortality of 60%, but within different ranges, from 30% to 100% for the former and 31% to 77% for the latter. Año Nuevo had the lowest average mortality of 55%

within a wide range of 6% to 100% among the 11 planting units (Fig. 3)

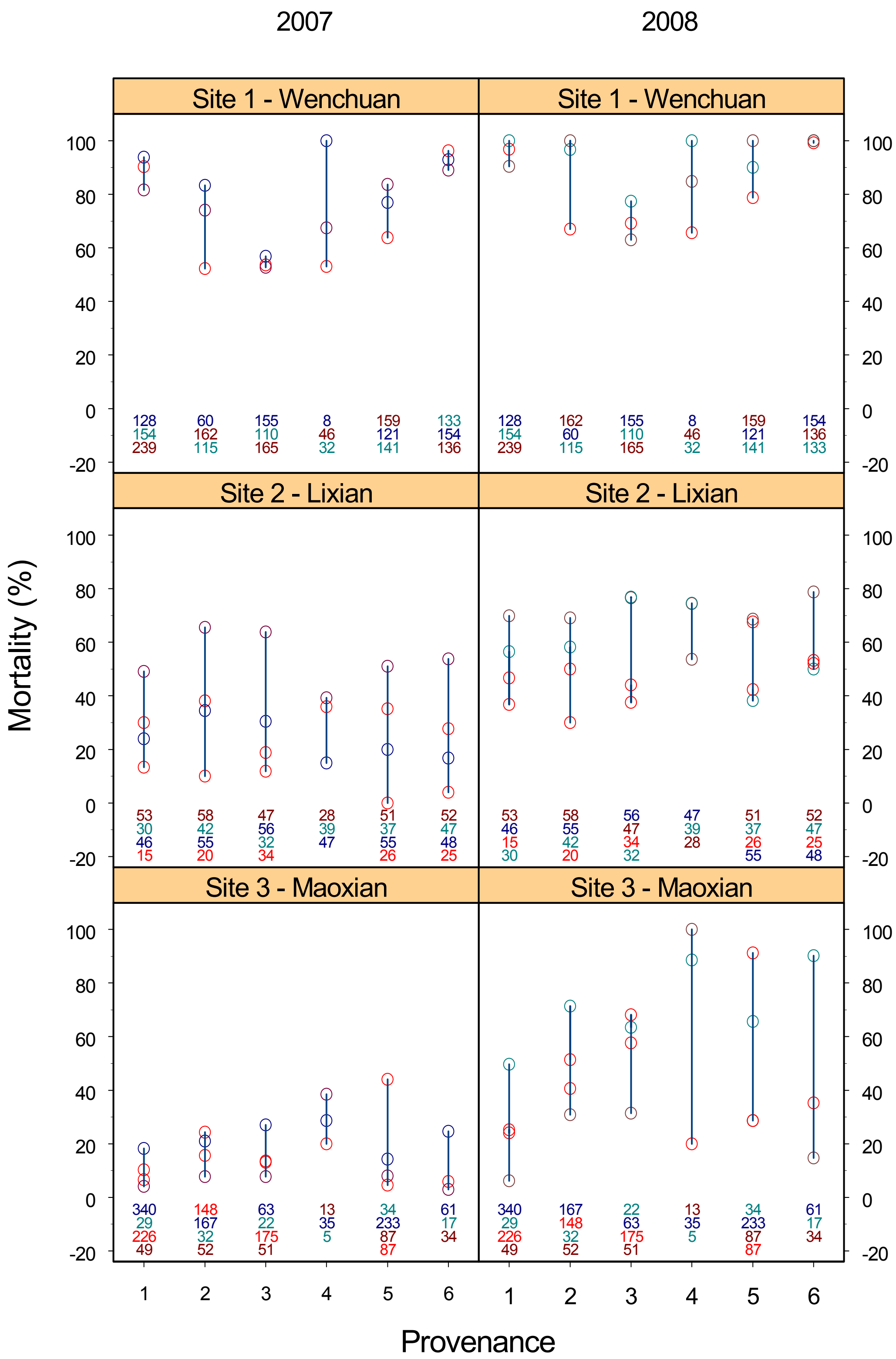

Fig. 3 Multipanel display of mortality levels of the six provenances across the three experimental sites in 2007 and after the snowstorms and the devastating earthquake in 2008. Replicates for each provenance are shown in different colors in a panel, and the numbers at the bottom of the panel indicate the number of live trees in 2005 for the replicates.

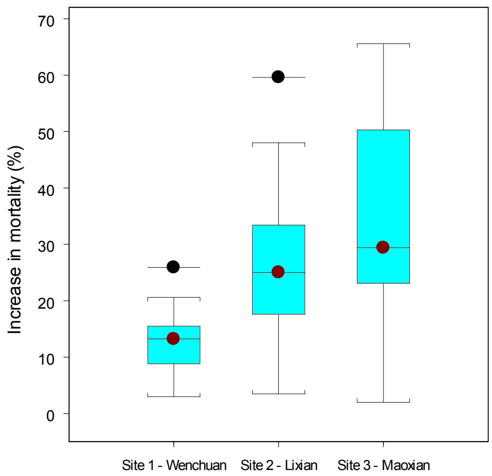

Fig. 4 Box-plots summarizing the increases in mortality of the 18, 23 and 22 provenance by replicate planting units at the first, second and third experimental site between 2007 and 2008 as shown in Fig. 3.

Growth performance

Tree growth was the best at the third site in Maoxian as shown by the site-level diameter, tree height and stem volume growth curves (Fig 5). The elevation and shape of these curves were determined by the estimated fixed-effect parameters including the overall intercept, the fixed effects of sites, the coefficients for the covariate of age and that for the interaction between site and age. The estimated coefficients for the interaction between site and age for the mean, median, the 75th and the 90th percentile of all three tree size variables for this site were significantly greater than that for the other two sites as indicated by the asymptotic t-tests. For example, the sum of the estimated coefficient for age and that for the interaction between site and age was 1.48 for the average diameter for this site, which was much greater than 0.98 and 1.12 for the first and second sites in Wenchuan and Lixian. With the sum of the two estimated coefficients being much greater than 1, the growth curve for the third site had a different shape to the other two sites (Fig. 5). The growth curves for the three sites increasingly diverged as the trees grew over time. Pairwise comparison of least square means at age one, just before planting, showed no significant differences between the sites for all tree size variables. At age six, the least square means of the three log transformed tree size variables for the third site were significantly greater than that for the other two sites, except for the mean and the 90th percentile of tree height which were significantly greater than the second site, but not the first site. In comparison, the differences in the least square means between the first and the second site at the same age were not as large in magnitude, but nonetheless, statistically significant for a number of tree size variables. The second site had significantly larger values for the average, median and the 75th percentile of diameter, and significantly smaller 90th percentile of tree height than the first site. Consequently, the 50th and 75th percentile of nominal stem volume of the second site were also significantly larger than that of the first site (Fig. 5). These results suggested that tree growth were generally better at the second site in Lixian than at the first site in Wenchuan, except for the best trees as represented by the 90th percentiles of the three tree size variables.

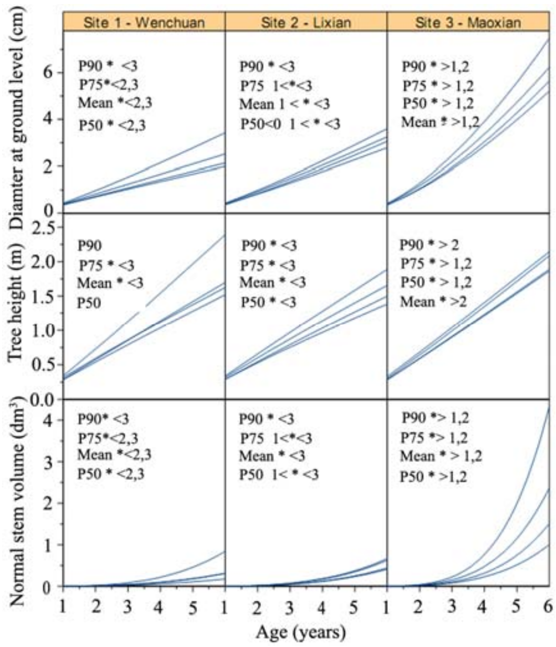

Fig. 5 Site level growth curves for the mean, the 50th, 75th and 90th percentiles of diameter, tree height and nominal stem volume. The positions of the four curves from top down are indicated by the order of the four symbols "Mean", "P50", "P75" and "P90" appearing in a column above the curves in each panel. Pairwise comparisons of least square means at age 6 years after germination (i.e. 5 years after planting) are shown alongside the column. The two symbols, "*<" and "*>", stand for significantly smaller and larger than the site number on the other side of the inequality sign at α=0.05 level.

The overall results of diameter, tree height and nominal stem volume growth suggested that the provenances were in three performance leagues (Figs. 6, 7). The first was led by Cambria and followed by Monterey. The second was led by the Australian landrace and followed by Guadalupe and Año Nuevo. Cedros was the lone worst performer in the third league. Cambria was the best performer among the six provenances across all sites as its growth curves of diameter, height and nominal stem volume were above that of all other provenances (Figs. 6, 7). Similar to the site-specific curves, the elevation and shape of these provenance-level curves were determined by the overall intercept, the fixed effects of sites and provenances, and the coefficients for the covariate of tree age and that for the interaction between site and age. At age six, the mean, the 50th, 75th and 90th percentile of diameter of Cambria were significantly greater than all other provenances, except for the 75th percentile which was not significantly greater than that of Monterey (Fig. 6). The results for tree height showed that Cambria was also significantly superior to all other provenances at age six, except for Monterey (Fig. 6). The differences in the least square means of the mean and me-

dian of nominal stem volume at age six between Cambria and other provenances were all significantly greater than zero. The nominal stem volume of the better than average and the best trees of Cambria as represented by the 75th and 95th percentiles were significantly larger than that of Año Nuevo, Cedros, Guadalupe and the Australian landrace, but not significantly larger than that of Monterey (Fig. 7).

Monterey was overall the second best performer behind Cambria. It was significantly superior to Año Nuevo, Cedros, Guadalupe and the Australian landrace for all tree size variables except for the 90th percentile of tree height, which was not significantly greater than the Australian landrace (Figs. 6, 7). The Australian landrace ranked the third in growth performance, although its best performing trees were not significant better than those of Guadalupe. Guadalupe was significantly superior to Año Nuevo in terms of the average tree size as shown by the results for the mean diameter and the mean and the 50th percentile of height and nominal stem volume. However, its best trees as represented by the 90th percentiles of the three tree size variables were not significantly difference from those of Año Nuevo. For all three tree size variables and their means and percentiles, the results showed that Cedros was significantly and consistently inferior to all other native provenances and the Australian land race.

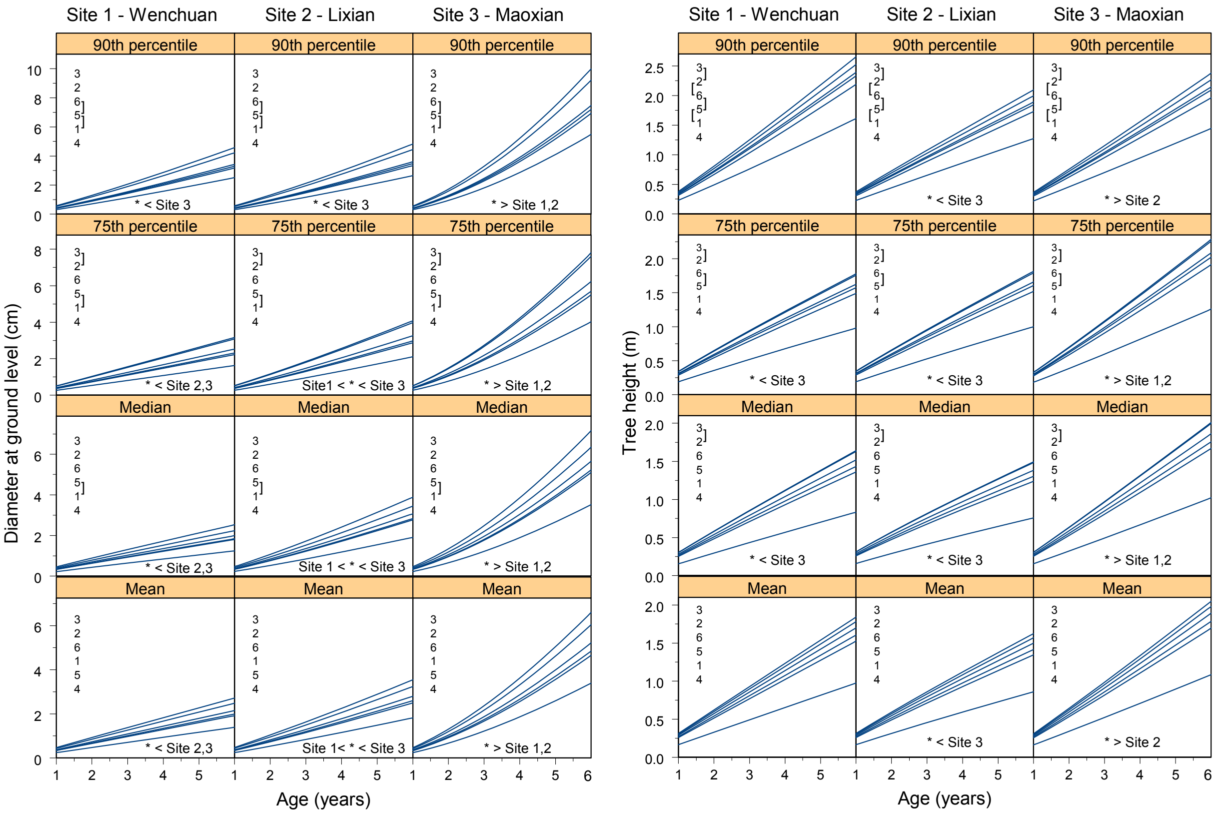

Fig. 6 Provenance level growth curves for the mean, the 50th, 75th and 90th percentiles of diameter (left) tree height (right) across the three experimental sites. The positions of the six curves from top down are indicated by the order of the six provenance codes appearing in a column dropping down from the top-left corner of each panel. Provenances connected by a square bracket are not significantly different from each other, while those unconnected are significantly different from each other at α=0.05 level. The symbols, "*<" and "*>", in the panels indicate significant site differences. Panels without these symbols indicate that there were no significant site differences.

Discussion

This provenance experiment in the dry river valley area is the latest and most likely the last experiment established using seeds from the 1978 collection participated and documented by Eldridge (1978, 1979). Since the seeds from the native populations had been stored for 25 years before being germinated for this experiment, the germination rates were low, but much better than what was expected by Eldridge (1997b), who speculated that the seeds would decline in viability and would be unlikely to germinate after 2010. There were noticeable variations in seed size, germination rate and in the size of seedlings among the six provenances, with Cendros having the lowest germination rate and smallest seedlings, and Cambria having the largest seedlings (Table 2). These differences could be partly due to the natural variation in cone and seed size among the provenances. The average cone size is very distinct among the native provenances of *P. radiata*, with Cambria having the largest cones and Cedros the smallest (Eldridge 1997b). These differences in seedling size

before planting could be attributable to the significant differences in early growth performance among the six provenances.

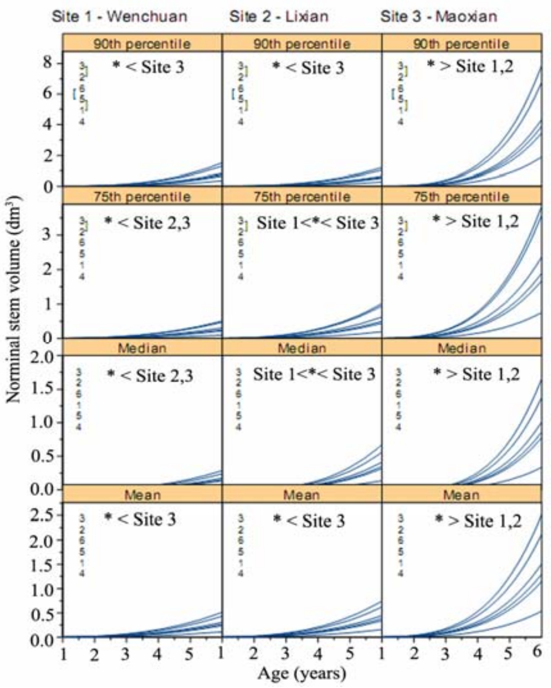

Fig. 7 Provenance level growth curves for the mean, the 50th, 75th and 90th percentiles of nominal stem volume across the three experimental sites. Provenance and site differences are indicated in the same way as in Fig. 6.

Comparing to other provenance trials of *P. radiata* established elsewhere in the 1980s using seeds from the same collection (see Toplu et al. 1987; Falkenhagen 1991; Jayawickrama and Balocchi 1993; Matziris 1995, Burdon et al. 1997; Johnson et al. 1997), the three experimental sites are in a summer rainfall environment with much lower soil nutrient and soil moisture supply and mean minimum temperatures in winter. The latter two are the limiting factors identified by Yan et al. (2006) for *P. radiata* over the entire course of the dry river valley area. At such difficult sites, it was naturally expected that the mortality would be much higher and growth rate much lower in comparison to the provenance trials in other countries. However, the cause of mortality was not the same across the sites. The high levels of mortality at the first site in Wenchuan were largely caused by weeds, which weakened the seedlings, and subsequently by insect infestations and finally by the earthquake in 2008. Insufficient soil moisture was the major cause of mortality at the second site in Lixian before the earthquake struck, while animal browsing and frost damage during the snowstorms in early 2008 led to the high level of mortality at the third site in Maoxian. These site-specific factors and disturbances would also impact on tree growth and therefore contribute to the significant growth differences across the three sites. Without animal browsing and frost damage, the better soil fertility and soil moisture conditions at the Maoxian site could have supported much better tree growth than the other two sites. Similarly, with better control of weeds and insect pests, the first site could be expected to have much better growth than the second and poorest site. As demonstrated by Rubilar et al. (2013), effective weed control can significantly boost the early growth of *P. radiata* largely by improving both the water and nutrient conditions for young trees.

The outstanding performance of Cambria at such difficult sites of this experiment added to the growing evidence that this provenance could grow well on low productivity sites. Similar results were first reported by Johnson et al. (1997) on two of the worst sites within a wide range of sites in New South Wales, Australia. Recent combined-analyses of provenance trials of *P. radiata* with mean annual rainfall ranging from 590 to 1600 mm in Australia and New Zealand at both juvenile age (8−12 years) and mature age (24−30 years) also revealed promising performance of Cambria at some sites (Gapare et al. 2011, 2012). The good performance of Monterey in this experiment suggested this provenance could grow much better than Año Nuevo at dry and infertile sites. The suitability of Monterey for infertile sites was also reported by Shelbourne et al. (1979) and Burdon et al. (1997) in New Zealand. The findings of many previous studies were that Monterey along with Año Nuevo were the overall best performers for growth over a range of sites well-suited to growing *P. radiata* for timber production (Burdon 1992; Jayawickrama and Balocchi 1993; Burdon et al. 1997; Johnson et al. 1997; Gapare et al. 2011, 2012). These studies also showed that Año Nuevo tended to have better growth on high productivity sites and was the most interactive. The poor performance of Año Nuevo in this experiment might be due to its inability to adapt to low productivity sites as well as its interactive nature, although no significant site and provenance interaction was detected at the early stage of growth in this study.

Being inferior to Monterey and superior to Año Nuevo, the performance of the Australian landrace was an interesting result from this experiment since its genetic base was Año Nuevo and Monterey, the two supposedly best-adapted of the five natural populations to a wide range of plantation sites in Australia. The genetic improvements realised from the Tallaganda seed orchard, from which seeds for the Australian landrace were collected, yielded about 20% more total wood volume in three yield trials at 10−12 years of age, with about twice as many trees of excellent stem and branch quality, than a control seedlot representing the population from which the trees in the orchard were selected (Eldridge 1982; Wright and Eldridge 1985). The improvements were thought to be attributable to the intensive phenotypic selection of plus-trees followed by mating among the clones in the orchard (Eldridge 1982). However, the results of this experiment suggested that such improvements obtained on high productivity sites might not be realised at low productivity sites.

The superiority of Guadalupe to Año Nuevo was a result from this experiment that differed from the findings of previous studies that the island provenances were significantly inferior to all the mainland provenances at eight trial sites across three states in Australia (Gapare et al. 2012). Guadalupe was also significantly better than Cedros, which was consistently inferior to all other native provenances and the Australian land race. Although not based on formal statistical analysis, Cedros suffered the highest level of mortality among the six provenances. The particularly

low survival rate of Cedros was also observed in Greece (Matziris 1995), and in several provenance trials in Australia at ages between 8 and 12 years (Gapare et al. 2011). The high mortality rate of Cedros could be attributed to its smaller seedling size at the time of planting (Table 2) and the slow growth compared to other provenances (Figs. 6, 7). In comparison to other provenances, the genetic base of Cedros was much narrower and possibly inferior as there was no opportunity to select seeds from the largest trees with good form during seed collection and only about 1 kg of seeds were collected from 51 trees on the Cedros Island in 1978. Furthermore, evolutionary history based on fossil record of pine cones and the genetic structure of *P. radiata* populations suggested that Cedros could be the most primitive line that separated from the rest of the geographical range of *P. radiata* several million years ago and it has been restricted in the recent evolutionary past since the separation (Axelrod 1980, Moran et al. 1988).

Since seeds of *P. radiata* for the current environmental planting in the dry river valley area were sourced from either New Zealand or Australia where the genetic base was derived largely from Año Nuevo and Monterey, the low ranking of the Australian landrace among the six provenances suggests that the planting stock may not be the most suitable to the growing environment. If so, Cambria and Monterey should be considered as the genetic base for future tree breading to develop genotypes that are most suitable for this particular area. Because the genetic base of the present Australian plantations was derived largely from Año Nuevo and Monterey, the superior early growth performance of Cambria at such difficult sites of this experiment presents a new promise to the search of *P. radiata* provenances for the vast dryland areas in New South Wales and other parts of Australia for the combined purpose of timber production and carbon farming.

Although a clear ranking of the six provenances was established, it should be kept in mind that the results of this experiment were based on their early growth only. As trees grow over time, the ranking order or the level of significance of the observed growth differences may change. For example, Burdon et al. (1992) reported no significant differences between the mainland provenances for height or DBH at early age, but by the age of 12 years, Cambria had dropped behind Año Nuevo and Monterey. On the other hand, Gapare et al. (2012) showed that provenance rankings across sites observed at juvenile ages were similar to those observed at mature ages. A change in the ranking order among the six provenances can occur through either further divergence or convergence of the growth curves over the next two or three decades. Therefore every effort should be made to maintain and measure the part of the experiment that remained intact after the devastating 2008 earthquake for the next twenty years at least.

Acknowledgements

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